

IS CALVERA A GAMMA-RAY PULSAR?

J. P. HALPERN

Astronomy Department, Columbia University, 550 West 120th Street, New York, NY 10027-6601, USA; jules@astro.columbia.edu
(Received 2011 March 16; Accepted 2011 June 10)

ABSTRACT

Originally selected as a neutron star (NS) candidate in the ROSAT All-Sky Survey, 1RXS J141256.0+792204 (“Calvera”) was discovered to be a 59 ms X-ray pulsar in a pair of *XMM-Newton* observations (Zane et al. 2011). Surprisingly, their claimed detection of this pulsar in *Fermi* γ -ray data requires no period derivative, severely restricting its dipole magnetic field strength, spin-down luminosity, and distance to small values. This implies that the cooling age of Calvera is much younger than its characteristic spin-down age. If so, it could be a mildly recycled pulsar, or the first “orphaned” central compact object (CCO). Here we show that the published *Fermi* ephemeris fails to align the pulse phases of the two X-ray observations with each other, which indicates that the *Fermi* detection is almost certainly spurious. Analysis of additional *Fermi* data also does not confirm the γ -ray detection. This leaves the spin-down rate of Calvera less constrained, and its place among the families of NSs uncertain. It could still be either a normal pulsar, a mildly recycled pulsar, or an orphaned CCO.

Subject headings: pulsars: individual (1RXS J141256.0+792204, PSR J1412+7922, Calvera) — stars: neutron

1. INTRODUCTION

The NS candidate 1RXS J141256.0+792204, dubbed “Calvera” (Rutledge et al. 2008), was selected from the *ROSAT* All-Sky Survey, and observed by *Chandra* (Rutledge et al. 2008; Shevchuk et al. 2009). A deep radio pulsar search showed that it is radio quiet (Hessels et al. 2007). It was not until a pair of *XMM-Newton* observations was obtained with high time resolution that Zane et al. (2011) discovered 59 ms pulsations from Calvera. The classification of Calvera among the families of NSs is not yet understood. Its X-ray spectrum is characterized as a blackbody of temperature ≈ 0.2 keV, or a hydrogen atmosphere of $T \approx 0.1$ keV (Shevchuk et al. 2009; Zane et al. 2011). Two-temperature models provide a better fit, and the surface temperature must be nonuniform because pulsations are seen. Calvera’s properties distinguish it from seven isolated NSs (INSs: Haberl 2007), also discovered by *ROSAT*, which are slowly rotating ($P = 3 - 11$ s), cooler NSs in the solar neighborhood. X-ray timing and spectroscopy and kinematic studies of the INSs indicates that they have strong magnetic fields, $B_s \approx 2 \times 10^{13}$ G, and are $\approx 10^6$ years old (Kaplan & van Kerkwijk 2009). Calvera is at least twice as hot as the INSs, indicating an age $\leq 10^5$ yr according to minimal NS cooling curves (Page et al. 2004, 2009). Even though it is at high Galactic latitude ($\ell, b = (118^\circ, +37^\circ)$), if Calvera is a passively cooling NS it must be close to its birth place in the disk, implying a maximum distance of a few hundred parsecs. Depending on the X-ray spectral model fitted, the column density is consistent with a range of values that does not further constrain the distance. Based on the spectral fits of Zane et al. (2011), the bolometric flux is uncertain by about a factor of 2, and the luminosity is $L_X \approx 1.7 \times 10^{31} d_{300}^2 \text{ erg s}^{-1}$, where d_{300} is the distance in units of 300 pc. Calvera remains radio quiet even after a deeper search for radio pulsations at 59 ms (Zane et al. 2011).

Analyzing data from the *Fermi* Large Area Telescope (LAT), Zane et al. (2011) claimed that 59 ms pulsations are detected from 1RXS J141256.0+792204 at > 100 MeV. Apart from the marginal significance of the detection, this result is surprising because their ephemeris requires no frequency derivative over the 21 month time span analyzed. Their effective 2σ upper limit is $|\dot{f}| < 2.6 \times 10^{-16} \text{ Hz s}^{-1}$, implying spin-down power $\dot{E} = -4\pi^2 I f \dot{f} < 1.7 \times 10^{32} \text{ erg s}^{-1}$, characteristic age $\tau_c \equiv -f/2\dot{f} > 1.0 \times 10^9 \text{ yr}$, and magnetic field strength $B_s = 3.2 \times 10^{19} \sqrt{-\dot{f} f^{-3}} < 7.4 \times 10^9 \text{ G}$. Here we assume a moment of inertia $I = 10^{45} \text{ g cm}^2$, B_s is the equatorial surface dipole field, and frequency $f = 16.89 \text{ Hz}$. (We are unable to account for their quoted upper limit $B_s < 5 \times 10^{10} \text{ G}$, which would allow $\dot{f} = -1.2 \times 10^{-14} \text{ Hz s}^{-1}$.)

These timing parameters imply that 1RXS J141256.0+792204 is not just a passively cooling NS, but is converting a large fraction of its meager spin-down power into γ -rays. The quoted pulsed γ -ray luminosity is $L_\gamma \approx 1.5 \times 10^{32} d_{300}^2 \text{ erg s}^{-1}$ assuming isotropic emission. All other γ -ray pulsars have $\dot{E} > 2 \times 10^{33} \text{ erg s}^{-1}$ (Abdo et al. 2010a); Calvera would be the least energetic γ -ray pulsar by an order of magnitude. In this Letter, we show that the *Fermi* detection of Calvera is almost certainly false. We then discuss the implications for the nature of Calvera.

2. XMM-NEWTON TIMING OF THE PULSATIONS FROM 1RXS J141256.0+792204

We reduced the now archival EPIC pn CCD data from the two *XMM-Newton* observations of Calvera listed in Table 1. These were taken in small window mode with 5.7 ms time resolution, and were separated by 40 days. The data were processed with SAS version xmm-sas_20090112_1802-8.0.0. We extracted photons in the 0.15 – 2 keV band from a $20''$ radius aperture around

Table 1
XMM-Newton EPIC pn Timing of 1RXS J141256.0+792204

| ObsID | Date (UT) | Date (MJD) | Span (s) | Exp. (s) | Frequency (Hz) ^a | Z_1^2 |
|------------|-------------|------------|----------|----------|-----------------------------|---------|
| 0601180101 | 2009 Aug 31 | 55,074.30 | 19,911 | 13,941 | 16.8924052(25) | 141.1 |
| 0601180201 | 2009 Oct 10 | 55,114.18 | 27,816 | 19,477 | 16.8924041(15) | 201.9 |

^a 1 sigma error in parenthesis.

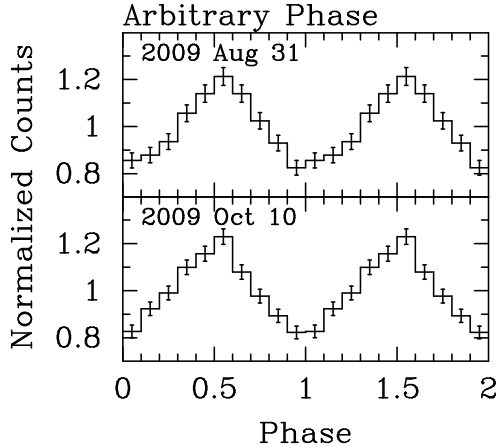


Figure 1. The two *XMM-Newton* pulse profiles of 1RXS J141256.0+792204 in the 0.15 – 2 keV band, each folded on its peak frequency from Table 1, and aligned arbitrarily in phase. Background has been subtracted and the counts are normalized to 1. Two cycles are plotted.

the source. Background was taken from an adjacent region on the CCD. We applied the conversion to Barycentric Dynamical Time using the precise *Chandra* position of the source from Shevchuk et al. (2009), R.A. = $14^{\text{h}} 12^{\text{m}} 55^{\text{s}}.84$, Decl. = $+79^{\circ} 22' 03''.7$ (J2000.0). The $0''.6$ position uncertainty is a negligible source of error on the absolute timing. Table 1 lists the peak frequencies of the two *XMM-Newton* observations derived from a Z_1^2 power spectrum (Rayleigh test; Strutt 1880; Buccheri et al. 1983). We folded each light curve at the peak period. The pulse profiles are shown in Figure 1, where we have aligned them arbitrarily in phase. The two profiles have a consistent, quasi-sinusoidal or triangular shape, and a pulsed-fraction of $\approx 18\%$. The precise agreement between the frequencies at the 10^{-7} fractional level argues against any orbital motion (but see below), which is supported by the absence of an optical counterpart.

As noted by Zane et al. (2011), the precision of the two frequency measurements is insufficient to join these widely spaced observations coherently and obtain more precise timing parameters. Since the measured frequencies agree within their errors, we can only derive an upper limit on the spin-down rate. Using the data in Table 1, we calculate an upper limit on the frequency derivative by propagating the errors and dividing the difference of the frequencies by the time interval between the observations. The 2σ upper limit is $|\dot{f}| < 2.0 \times 10^{-12} \text{ Hz s}^{-1}$. The corresponding 2σ limits on the spin-down properties are $\dot{E} < 1.3 \times 10^{36} \text{ erg s}^{-1}$, $\tau_c > 1.3 \times 10^5 \text{ yr}$, and $B_s < 6.5 \times 10^{11} \text{ G}$. These are the limits that we will conclude are the best currently available. They are consistent with the Zane et al. (2011) results of the same

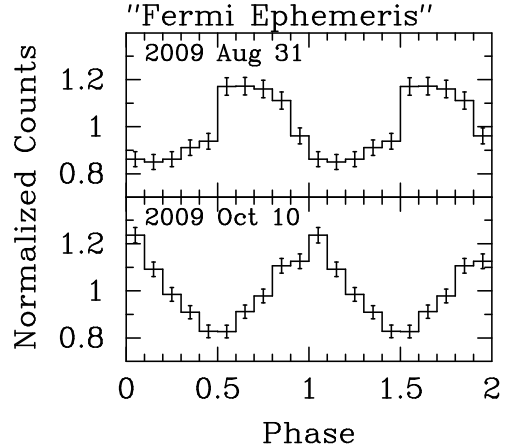


Figure 2. The same data as in Figure 1, now folded on the supposed *Fermi* ephemeris (Zane et al. 2011) that spans these epochs (see text). The bin size of the 10 bin light curve is 5.9 ms, comparable to the CCD frame time of 5.7 ms. Evidently the ephemeris does not phase-align the X-ray pulse profiles.

analysis.

Using *Fermi* LAT data, Zane et al. (2011) claimed to detect γ -ray pulsations from 1RXS J141256.0+792204 by searching coherently a 21 month span from 2008 August to 2010 April using the Z_1^2 test. Although no imaging detection of a source at this position was reported, searching both f and \dot{f} around the X-ray measured values, they found a peak power $Z_1^2 = 26.2$ with the following ephemeris: epoch $t_0 = 55094 \text{ MJD}$, $f = 16.892401975(2) \text{ Hz}$, $\dot{f} = -1.2(7) \times 10^{-16} \text{ Hz s}^{-1}$. Since this ephemeris spans the dates of the *XMM-Newton* observations in 2009 August and October, it can be used to fold the X-ray photons, and the pulse profiles so derived should align in phase. Zane et al. (2011) did not perform this test. The result is shown in Figure 2. The test fails because the light curves folded according to the trial ephemeris are out of phase by 0.35 cycles (21 ms). As we discuss below, this is much larger than the maximum $\sim 3 \text{ ms}$ uncertainty due to the 5.7 ms CCD frame time. Therefore, we conclude that the ephemeris represents a noise peak in the power spectrum of (probably) background photons, not a true detection of pulsations.

This test does not involve the phasing of the γ -ray pulse with respect to the X-ray pulse, nor is it sensitive to uncertainties on the *Fermi* ephemeris parameters. This is because the coherent ephemeris is a *phase* ephemeris. It specifies the phase of the pulsar $\phi(t) = f(t - t_0) + (1/2)\dot{f}(t - t_0)^2$ at all times during the span of the ephemeris, and the *XMM-Newton* observations are contained well within that span. The quoted *Fermi* uncertainties, $\sigma_\gamma(f) = 2 \times 10^{-9} \text{ Hz}$ and $\sigma_\gamma(\dot{f}) = 7 \times 10^{-17} \text{ Hz s}^{-1}$, can contribute only tiny drifts in relative phase, $\Delta\phi = \sigma_\gamma(f) T_X = 0.007 \text{ cycles}$

and $\Delta\phi = 0.5\sigma_\gamma(\dot{f})T_X^2 = 0.0004$ cycles, respectively, over the $T_X = 40$ day interval between the X-ray observations. Even these are upper limits, as the errors are covariant.

Our analysis does depend on the stability of EPIC pn timing in small window mode. Considerable effort has gone into calibrating the relative and absolute timing of this particular mode and maintaining the accuracy of the photon time assignments in the processing chain. The absolute accuracy of the *XMM-Newton* clock is better than 0.6 ms (Kirsch et al. 2004). We have carried out extensive investigations of pulsars using the pn small window mode, and empirical checks for consistency show that the absolute times are at least as accurate as the ~ 3 ms uncertainty due to the 5.7 ms CCD frame time. We summarize two of these studies here: A coherent ephemeris for the 237 ms pulsar Geminga using 10 *XMM-Newton* observations over a span of 7 years has phase residuals of 2 ms. We have used it to demonstrate the stable phase relationship between the X-ray and γ -ray pulse of Geminga with *AGILE* (Pellizzoni et al. 2009) and *Fermi* (Abdo et al. 2010b) to < 1 ms. These agree with earlier results comparing EGRET and *ASCA* (Jackson & Halpern 2005). In an extensive campaign on the 105 ms pulsar PSR J1852+0040 (Halpern & Gotthelf 2010), 16 *XMM-Newton* observations and seven *Chandra* observations (with time resolution 3 ms) spanning 4.8 years are fitted by a quadratic phase ephemeris with rms phase residuals of 3.4 ms. This demonstrates that *XMM-Newton* and *Chandra* agree in absolute time to better than 3 ms.

Our analysis does not make use of the EPIC MOS detector timing data that were obtained simultaneously with the pn. Zane et al. (2011) noted that the MOS detector's timing mode is not well calibrated, and they did not use it for timing analysis.

3. DISCUSSION OF PREVIOUS FERMI ANALYSIS

We address here reasons why one might consider the *Fermi* detection of Calvera to be real despite our negative evidence. First, Zane et al. (2011) suggest that actually a more conservative upper limit on the frequency derivative from *Fermi* should be allowed, $|\dot{f}| < 10^{-15}$ Hz s $^{-1}$. Still, its effect over the 40 day interval between X-ray observations would be negligible, and it would not change the outcome of our X-ray phase comparison. It is not clear why they entertain this possibility, since such a value would contribute 1.5 extra cycles of rotation over the 21 month span of their ephemeris. If \dot{f} actually turns out to be -1×10^{-15} Hz s $^{-1}$, it would be a different ephemeris from the published one, and the claimed detection would be spurious. For that matter, the frequency of the pulsar could also turn out to differ by more than one Fourier bin ($1/T_\gamma$, where T_γ is the 21 month span of the *Fermi* data) from the published *Fermi* ephemeris, and still be consistent with the X-ray measured value. In this case as well, the claimed γ -ray detection is just noise.

Second, it may be argued that, while the fitted ephemeris corresponds to the average values of f and \dot{f} over the time span, there could be timing noise that smears the pulse, while the signal is not strong enough to fit such trends with higher order terms. Under this hy-

pothesis, the phase drift between the two X-ray observations is a manifestation of timing noise. We consider this unlikely because the fitted \dot{f} is already consistent with zero. Any detectable timing noise would vary the sign of \dot{f} , which has not been seen in any isolated pulsar apart from glitch discontinuities. A phase drift of 0.35 cycles over 40 days would require an effective $\dot{f} = -5.9 \times 10^{-14}$ Hz s $^{-1}$ over this time, almost 500 times the mean value of -1.2×10^{-16} Hz s $^{-1}$. This seems unlikely, as does a glitch that is not also detected in the γ -ray timing. No pulsar with $\tau_c > 20$ Myr has been observed to glitch (Espinoza et al. 2011).

As an alternative to timing noise, it may be hypothesized that the X-ray phase shift over 40 days is evidence of binary motion, i.e., a planetary companion. Such an explanation would require the orbital period to be much less than the 21 month span of the *Fermi* ephemeris, but longer than the durations of the individual *XMM-Newton* pointings, which are 5.5 hours and 7.7 hours, respectively. We consider that $1 \text{ day} < P_{\text{orb}} < 100 \text{ days}$ covers the applicable range. Under the binary hypothesis, the projected radius $a_{\text{ns}} \sin i$ of the NS orbit falls in a narrow range. The Roemer delay $2a_{\text{ns}} \sin i/c$ must be ≥ 21 ms to produce the phase shift, but ≤ 59 ms so as not to smear out the supposed γ -ray pulsations. Combining these requirements, for $m_{\text{ns}} = 1.4 M_\odot$ we find that

$$20 M_\oplus < \left(\frac{P_{\text{orb}}}{100 \text{ days}} \right)^{2/3} m_p \sin i < 60 M_\oplus.$$

This corresponds to a minimum planet mass of $m_p = 20/\sin i$ Earth masses, and a maximum of $4/\sin i$ Jupiter masses, the latter for $P_{\text{orb}} = 1$ day. More likely the γ -ray ephemeris is spurious, and the 0.35 cycle phase shift is a random number, not evidence of a planet.

Other aspects of the Zane et al. (2011) analysis are unusual. By their own description, the γ -ray signal is marginal, with $Z_1^2 = 26.2$, and its significance depends on the number of independent trials in the search. The trials can be assessed using the X-ray uncertainties on the timing parameters in Section 2, $\sigma_X(f) = 1.5 \times 10^{-6}$ Hz and $\sigma_X(\dot{f}) = 1 \times 10^{-12}$ Hz s $^{-1}$, and the $T_\gamma = 21$ month span of the *Fermi* data. The number of independent trials in the two-dimensional *Fermi* search should be at least $4\sigma_X(f)T_\gamma \approx 330$ for frequency, and $\sigma_X(\dot{f})T_\gamma^2 \approx 3000$ for frequency derivative. These represent a search of independent frequencies in the $\pm 2\sigma$ interval around the *XMM-Newton* measured f , and independent frequency derivatives ranging from zero to the -2σ limit, i.e., only negative \dot{f} . If so, the expected number of noise peaks of power $Z_1^2 \geq 26.2$, obtained by multiplying the 1×10^6 trials by the single-trial probability, $e^{-26.2/2} = 2 \times 10^{-6}$, is of order unity. The oversampling by a factor of 10 that was performed further reduces the statistical significance. The crux of their argument must be that, since the value of \dot{f} in the discovered signal is consistent with zero, almost no trials in \dot{f} were needed to find it. Only this would allow that the chance probability of the result is $\sim 7 \times 10^{-4}$. But they do not display the power spectrum for the complete search. Instead, they say that they did not find false detections over a range of parameters much wider than the X-ray uncertainties. It is not

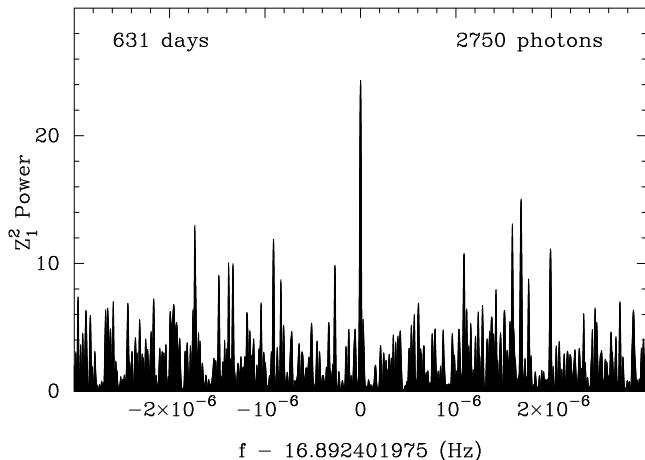


Figure 3. Power spectrum of *Fermi* data covering the time span analyzed by Zane et al. (2011), 2008 August 4 – 2010 April 27. The peak power $Z_1^2 = 24.4$ is similar to their value of 26.2. The two-dimensional search in f and \dot{f} was projected onto one dimension in this plot.

stated what they consider a false detection, and we are not shown the values of the highest peaks in the extended search. Therefore, we don’t know what to make of this argument. Finally, the absence of the γ -ray source in a spatial image is also worrisome, especially since the position is at high Galactic latitude with minimal confusing diffuse background. So there is no supporting evidence of a source at this position.

4. ANALYSIS OF NEW FERMI DATA

For completeness, we extracted and reduced *Fermi* data using the same event filtering and methods described by Zane et al. (2011). We first extracted the identical 631 day time span, 2008 August 4 – 2010 April 27, recovering 2750 photons, similar to their 2518 photons. A Z_1^2 search covering their $\pm 3\sigma$ range of *Fermi* frequency derivative recovers the candidate peak at $f = 16.892401976$, as shown in Figure 3. The peak power, $Z_1^2 = 24.4$, is consistent with their value of 26.2.

We then applied the same method to the full data set now available, comprising 4764 photons collected up to 2011 May 19 (33 months). This increases the number of photons by 73%. A search of the same ephemeris parameters does not yield increased power at the claimed frequency. Rather, the peak previously seen is reduced to $Z_1^2 = 16.0$ (Figure 4), indicating that it was just noise. We regard this result as direct support of our inference that the supposed *Fermi* detection was not real. A wider search of thousands of trials in \dot{f} is not meaningful, for the reasons discussed above.

5. CONCLUSIONS

In summary, the incorrect phasing of the X-ray observations of Calvera using the claimed *Fermi* ephemeris led us to conclude that the γ -ray detection is probably spurious. Then, extending the *Fermi* analysis from 21 to 33 months rendered the candidate signal insignificant. Here we comment on the implications for the nature of Calvera of the less restrictive 2σ limit $|\dot{f}| < 2.0 \times 10^{-12} \text{ Hz s}^{-1}$ from X-ray timing. The corresponding limits on spin-down properties, $\dot{E} < 1.3 \times 10^{36} \text{ erg s}^{-1}$, $\tau_c > 1.3 \times 10^5 \text{ yr}$,

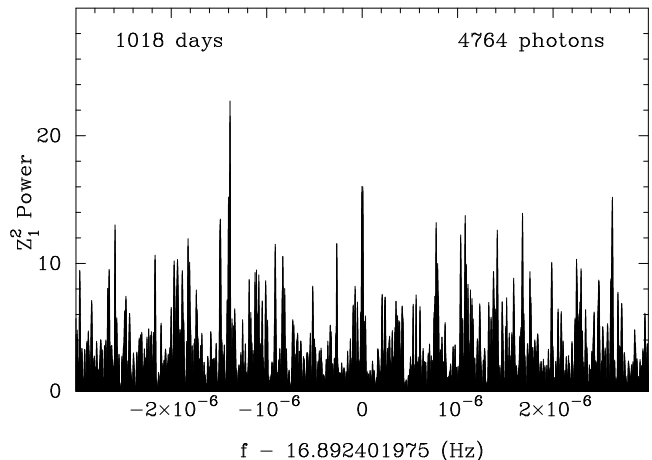


Figure 4. Power spectrum of *Fermi* data covering an extended time span, 2008 August 4 – 2011 May 19, showing that the peak in Figure 3 is no longer significant.

and $B_s < 6.5 \times 10^{11} \text{ G}$, allow three scenarios. First, Calvera could be an ordinary pulsar with magnetic field strength 1.5σ or more below the mean of the birth distribution (Faucher-Giguère & Kaspi 2006). Second, it could be a mildly recycled pulsar, formerly in a binary system with a high-mass companion that has since undergone a supernova explosion. In this case, its magnetic field strength would be intermediate between those of fully recycled (millisecond) pulsars, and ordinary pulsars. Third, it could be an “orphaned CCO” as we describe next. The second and third scenarios were also addressed by Zane et al. (2011).

The class of central compact objects (CCOs) in supernova remnants comprises ≈ 10 NSs, three of which are detected pulsars with $P = 0.1 - 0.4 \text{ s}$. See Halpern & Gotthelf (2010, 2011) and Gotthelf et al. (2010) for observations and overview of related theory. The CCO pulsars have weak dipole fields, in the range $10^{10} - 10^{11} \text{ G}$, and negligible spin-down power in comparison with their bolometric X-ray luminosities of $10^{33} - 10^{34} \text{ erg s}^{-1}$. These $10^3 - 10^4 \text{ yr}$ old NSs must represent a significant fraction of NS births. After their host supernova remnants dissipate, orphaned CCOs will remain in the region of (P, \dot{P}) space where they were born, which is also where the supposed mildly recycled pulsars are found (Belczynski et al. 2010). An orphaned CCO would be distinguished from a single, recycled pulsar by its residual thermal X-ray luminosity. An orphaned CCO could be recognized as a thermal X-ray source, depending on its distance, while it is up to $10^5 - 10^6 \text{ yr}$ old (not the characteristic age, which is orders of magnitude larger than the real age of a CCO). The known CCOs have X-ray temperatures in the range $0.2 - 0.4 \text{ keV}$. Calvera, being cooler than this and less luminous than a young CCO by an order of magnitude or more, could be an evolved stage of a passively cooling CCO. It is possible, therefore, that 1RXS J141256.0+792204 is the first orphaned CCO to be recognized.

These scenarios can be distinguished by the spin-down rate of the pulsar. If $B_s = 6 \times 10^{11} \text{ G}$ and $\tau_c = 1.5 \times 10^5 \text{ yr}$, Calvera is probably an ordinary pulsar. If $B_s = 1 \times 10^{11} \text{ G}$ and $\tau_c = 4 \times 10^6 \text{ yr}$, it could be an orphaned CCO younger than τ_c , or a spin-powered, mildly

recycled pulsar. If $B_s = 1 \times 10^{10}$ G and $\dot{E} = 3 \times 10^{32}$ erg s $^{-1}$, its spin-down power is probably insufficient to heat its surface, and an orphaned CCO would be required instead of a mildly recycled pulsar to explain its X-ray luminosity and temperature. Even though Calvera is not (yet) detected in γ -rays, an X-ray timing study is straightforward, and should detect its spin-down in ≈ 1 yr even if its magnetic field strength is only $\approx 10^{10}$ G.

We thank Eric Gotthelf for discussions and assistance with the data. This investigation is based on observations obtained with *XMM-Newton*, an ESA science mission with instruments and contributions directly funded by ESA Member States and NASA.

REFERENCES

- Abdo, A. A., et al. 2010a, *ApJS*, 187, 460
 Abdo, A. A., et al. 2010b, *ApJ*, 720, 272
 Belczynski, K., Lorimer, D. R., Ridley, J. P., & Curran, S. J. 2010, *MNRAS*, 407, 1245
 Buccheri, R., et al. 1983, *A&A*, 128, 245
 Espinoza, C. M., Lyne, A. G., Stappers, B. W., & Kramer, M. 2011, *MNRAS*, 414, 1679
 Faucher-Giguère, C.-A. & Kaspi, V. M. 2006, *ApJ*, 643, 332
 Gotthelf, E. V., & Perna, R., & Halpern, J. P. 2010, *ApJ*, 724, 1316
 Haberl, F. 2007, *Ap&SS*, 308, 181
 Halpern, J. P., & Gotthelf, E. V. 2010, *ApJ*, 709, 436
 Halpern, J. P., & Gotthelf, E. V. 2011, *ApJ*, 733, L28
 Hessels, J. W. T., Stappers, B. W., Rutledge, R. E., Fox, D. B., & Shevchuk, A. H. 2007, *A&A*, 476, 331
 Jackson, M. S., & Halpern, J. P. 2005, *ApJ*, 633, 1114
 Kaplan, D. L., & van Kerkwijk, M. H. 2009, *ApJ*, 705, 798
 Kirsch, M. G. F., et al. 2004, in *Proc. SPIE 5165, X-ray and Gamma-Ray Instrumentation for Astronomy XIII*, ed. K. A. Flanagan & O. H. W. Siegmund (Bellingham, WA: SPIE), 85
 Page, D., Lattimer, J. M., Prakash, M., & Steiner, A. W. 2004, *ApJS*, 155, 623
 Page, D., Lattimer, J. M., Prakash, M., & Steiner, A. W. 2009, *ApJ*, 707, 1131
 Pellizzoni, A., et al. 2009, *ApJ*, 691, 1633
 Rutledge, R. E., Fox, D. B., & Shevchuk, A. H. 2008, *ApJ*, 672, 1137
 Shevchuk, A. H., Fox, D. B., & Rutledge, R. E. 2009, *ApJ*, 705, 391
 Strutt, J. W. 1880, *Phil. Mag.*, 10, 73
 Zane, S., et al. 2011, *MNRAS*, 410, 2428